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Marine Biogeochemistry in the Coastal Arctic: Towards Improved Quantitative Understanding of the Controls on Marine Biogeochemical Processes in the Arctic Coastal Zone, and Their Impacts on Climate and the Food Web

A White Paper for DOE's Regional and Global Model Analysis (RGMA) Program

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Grand Challenges and Long-Term Goals

The Arctic is undergoing unprecedented environmental change and nowhere in the Arctic Ocean is this more evident and directly felt than along the coasts where people live, work, and come to visit. It is widely known that atmospheric CO_2 concentrations are increasing, temperatures are rising, sea ice is shrinking, permafrost is warming, and hydrological processes are being altered, although the resulting impacts of such changes on the Arctic marine carbon cycle, greenhouse gas (GHG) fluxes, ecosystems, toxic algal blooms and coastal communities are far from clear. Potential impacts include major threats such as severe ocean acidification (OA) and increased release of methane from coastal shelf seas, as well as shifts in primary production and food-web dynamics, which could in turn further accelerate environmental change.

The entire Arctic coastal zone is a dynamic and understudied region that is very likely to experience even larger changes yet due to complex physical and chemical interactions between the atmosphere, ocean, sea ice, sea bottom, land, rivers, and human presence. Arctic coastal communities fish and hunt for subsistence in regions coinciding with rapidly retreating sea ice, as well as expanding shipping routes, resource extraction and commerce. Considering also the prevalence of polynyas, input of terrestrial matter, riverine influences, and GHG release, coastal seas are of disproportionate importance from an Arctic marine biogeochemical perspective.

Coastal biogeochemical processes in the Arctic climate system and marine food web dynamics pose important research questions. Leveraging both Arctic modeling and observations will be necessary in order to identify the key marine biogeochemical components, along with their associated uncertainties. Similarly, an emphasis on model-data integration is critical to improve model parameterizations, mechanistic understanding of underlying processes, and predictions of future Arctic system dynamics. To do this successfully, the modeling and observational communities need to work together, following an integrated and iterative approach, from the earliest stages of research projects.

Grand Challenge 1. What are the key processes through which Arctic marine biogeochemistry impacts the climate system?

Marine biogeochemical processes that are important for the Earth's top-of-the-atmosphere radiative budget include those that affect surface albedo (coloration), cloud cover and brightness (biogenic aerosol emissions), and GHG concentrations (e.g., carbon sequestration, methane release). Long-term goals towards effectively incorporating these important processes into Earth system models include:

GC1.1: Identify the processes through which coastal and offshore Arctic marine biogeochemistry affects ocean heat and carbon storage, and the Earth's radiative balance, via impacts on surface albedo, cloud condensation nuclei (CCN) load, GHG concentrations, or other processes.

GC1.2: Quantify the potential impacts and their uncertainties of processes identified in GC1.1; rank these processes according to their potential importance (PI) and their uncertainty (U); and identify the processes that have highest PI and U.

GC1.3: Reduce uncertainties in the processes identified to have the highest PI and U, as identified in GC1.2 through targeted investigations combining field observations, satellite remote sensing observations, laboratory studies, and modeling.

Grand Challenge 2: What are the effects of ongoing and future change (warming land, loss of snow and ice) on nearshore Arctic biogeochemistry?

Part of the difficulty in understanding and predicting Arctic marine biogeochemical processes lies in the complex spatial heterogeneity and seasonal variability of the complex nearshore zone which encompasses river deltas, estuaries, and coastal seas. Terrestrial signatures have been found in the Arctic Basin, indicating that nearshore processes have the potential to impact offshore regions, but such studies are sparse and the extent of this influence is unknown. Long-term goals addressing the impact of future change on nearshore Arctic biogeochemistry include:

GC2.1: Identify the marine biogeochemical processes at the ice-ocean-land interfaces that are most impacted by climate change and ocean acidification.

GC2.2: Explore the effects of land (i.e., inputs from rivers and coastal erosion including heat, freshwater, carbon, nutrient, and sediment fluxes) on nearshore Arctic biogeochemistry.

GC2.3: Improve understanding of how physical, chemical, biological, and ecological changes associated with sea ice and snow variability impact nearshore Arctic biogeochemistry.

GC2.4: Explore how changes in freshwater (e.g., timing and magnitude) from glaciers, sea ice, rivers, groundwater, rain, and snow impact marine biogeochemistry through its impact on stratification, photosynthetic active radiation (PAR), nutrients, transport, dissolved organic matter (DOM), and timing of low pH events.

Grand Challenge 3. What are the key processes through which Arctic marine biogeochemistry impacts the food web in response to climate change?

Climate and biogeochemistry (GC1, GC2) are natural drivers of marine resources (e.g., ecosystems, food security, suitable habitats). Hence, changes in marine biogeochemical cycles, which connect the biotic and abiotic components of an ecosystem, will have repercussions for ecosystems and food webs, and vice versa. Tipping points are generally defined as a critical point(s) in forcing at which the future state or development of a system is qualitatively altered. Identifying elements that may be important in reaching tipping points of the Arctic marine ecosystem will be invaluable if we are to understand and quantify how the system may respond to climate change. New knowledge of key marine biogeochemical processes (e.g., GC1, GC2 and GC3) will be useful for predicting the vulnerability of fisheries and ecosystem services, and improving the resilience of communities that depend upon these resources.

GC3.1: Identify the processes through which Arctic marine biogeochemistry affects the food web through impacts on the timing, structure and functioning of marine food web dynamics, including production and carbon flow.

GC3.2: Quantify the potential impacts, and the associated uncertainties, of the processes identified in GC3.1; rank these processes according to their PI and their U.

GC3.3: Reduce uncertainties in the processes identified to have the highest PI and U, as identified in GC3.2, through targeted investigations combining field observations, satellite observations, laboratory studies, and modeling.

GC3.4: Recommend the required level of biogeochemical complexity needed in Earth system models and regional Arctic system coupled models to accurately deliver on questions relating to food web processes and even fisheries.

GC3.5 Establish a communications network that will facilitate deeper collaboration between members of the ocean and ice biogeochemistry and the ecosystem and food web modeling communities (including those using conceptual, ecological forecasting, and emergent modeling tools), such that overarching science questions linking climate, biogeochemistry and marine resources can more readily and efficiently be addressed.

Short-Term Goals

There are a number of activities we can develop in the next few years to advance the long-term goals of the Grand Challenges we identified above. Of benefit to all is improving communication between different research communities and projects, and supporting technical developments aimed at better integrating observations and modeling. Here, we detail short-term goals directed at these two endeavors. Subsequently, we present additional steps that can be carried out in the near term that will specifically address the long-term goals of the Grand Challenges.

Improve communication between different communities and projects:

Although it is common for researchers to do both modeling and measurements, they generally work with the tools and communities they are most familiar with. Efforts that generate collaboration among modelers and those who collect observational data are valuable as they help modelers understand the nuances and limitations of observational data that are used to develop and validate models. Likewise, if those who collect observational data become better educated about what types of data are lacking for developing robust models, new studies can be proposed that address current knowledge gaps. Such efforts should not underestimate the time required to develop cross-community collaborations. Iterations of in-person meetings may be required. In addition to integrated workshops that bring research communities together, other mechanisms for better integrating the modeling and observational communities include:

- Targeted grant funding supporting observers and modelers on the same project from the onset;
- Climate Process Teams (CPTs), which are small groups of observers, theoreticians, small-scale modelers, and other scientists working closely together to improve parameterizations of biogeochemical processes in Earth system models;
- Opportunities in the field that enable focused, in situ discourse about sampling strategies, possible guidance of field sampling strategies based on model simulations, and associated broader questions (e.g., during ramp ups of projects that focus on biogeochemical processes);
- Special sessions at scientific meetings on the topic of Arctic marine coastal biogeochemical modeling and observational synthesis;
- Regularly scheduled webinars with participants from both the modeling and observational communities (e.g., continuation of October and November 2018 IARPC webinar series: Current Capabilities for Including Biological Processes in Models and Opportunities to Use Associated Field Observations);
- Companion workshop(s) in conjunction with a science meeting (e.g., Ocean Carbon Biogeochemistry Meeting) or interdisciplinary forum (e.g., Forum for Arctic Modeling and Observational Synthesis (FAMOS)) where ideas, methods, and experiences are shared, providing an opportunity to engage a broad audience including international colleagues;

Technical goals:

Technical developments, such as community workspaces, shared drives, and publicly accessible databases, continue to improve and expand the ability of the research community to rapidly communicate and effectively collaborate. Technical developments that will aid the process include:

- Development of a comprehensive inventory of existing Arctic biogeochemical data sets originating from government, non-government, and academic sources;

- Formalize community agreement on a set of benchmarking standards to track skill improvements over time and across models;
- Propose a standard data format(s) (e.g., same scales, units, file type) that supports the sharing and usage of data (e.g., data combinations for interdisciplinary analyses);
- Develop sensitivity analyses and model diagnostic packages to identify key modeling parameters for targeted improvement;
- Quantify and prioritize observational uncertainties when integrating observations and modeling development;
- Establish a synthesis of current priorities, uncertainties, and maturity of marine biogeochemical processes considered to be of importance to climate, based on current knowledge (i.e., complete the draft Table 1 in Appendix);
- Populate the International Ocean Model Benchmarking (IOMB) Package https://pcmdi.github.io/CMEC/iomb.html and any other complementary model evaluation/diagnostic packages with standardized data sets;
- Advocate for consistent (core physical and biogeochemical) sampling across coastal Arctic systems;
- Advocate for a time-series approach to observational records, within the limitations of Arctic weather, to capture seasonal and inter-annual variability across the highly heterogeneous Arctic coastal zone;

Near term action items for addressing GC1:

- Identify processes likely to have the largest influence on climate and marine/ice ecosystem structure and functioning, based on current knowledge (e.g., see draft Table 1 in Appendix). Which are important? How might we determine their importance? (GC1.1 and GC3.3);
- Focus on improving specific processes in the models, using, e.g., sensitivity studies to target those with greatest uncertainty; and improving parameterizations at smaller and shorter time scales (GC1.2 and GC3.4);
- Identify additional process studies necessary to reduce uncertainties associated with important marine physical and biogeochemical processes in climate and food web models and their parameterizations (GC1.3 and GC3.5);

… for addressing GC2:

- Add biogeochemistry to rivers and riverine input into coastal ocean models (GC2.3 and GC3.1);
- Study how the relative magnitude of inputs from rivers and coastal erosion change across the nearshore Arctic, on seasonal and interannual scales, and how this affects biological production and inorganic carbon dynamics (e.g., effect on irradiance available

for primary production) (GC2.1-2.4);

- Explore terrestrial-ice-marine continuum DOM transformations that occur in Arctic coastal regions (GC2.2-2.4);

… for addressing GC3:

- Parameterize important ecosystem processes not included explicitly in models (e.g., sediment resuspension, bacterial grazing, respiration rates) and use polar or pertinent rates/parameters (GC3.1-3.2);
- Enhance understanding of how changes in marine biogeochemistry may be contributing to the northward spread and intensification of harmful algal blooms, and species shifts (GC3.3-3.5);
- Enhance understanding of the role of marine and ice biogeochemistry in determining marine coastal methane emissions, including net microbial methane metabolism at Arctic system component interfaces (GC3.1-3.3 and 3.5, and GC2.1);
- Enhance understanding of the role of nitrogen biogeochemistry in determining the relative abundance of marine nitrogenous nutrients (i.e., N_2 fixation, (de)nitrification, ammonification, deposition, advection, hydrology) at Arctic system component interfaces (GC3.1-3.3 and 3.5, and GC2.1);
- Determine carbonate saturation states and pH, which may not only be useful for assessing the vulnerability of fisheries to OA (GC3), but also the impact of OA on the bio-optical properties of sea and ice, generation of marine biogenic aerosols, carbon sequestration, and methane release, through changes in ecosystem community structure and function (GC1);

Current Research and Capabilities

Nearshore, coastal land-ice-ocean biogeochemical interactions is the major focus of the **NASA Arctic-COLORS Science Plan**, with proposed multiple locations from the Yukon River to the Mackenzie River, including measurements in large and small river systems, coastal lagoons, and coastal erosion sites, from the head of tidal influence to the coastal shelf. For reference see: https://arctic-colors.gsfc.nasa.gov/docs/ArcticCOLORS_Science_Plan_draft_January2018.pdf. Table 5.3 of the Arctic-COLORS Science Plan, which lists research groups and the processes they are focussing on with direct relevance to the Arctic coastal region, is included as Table 2 in the Appendix. The new **NSF LTER in the lagoons near Utqiagvik (aka Barrow) and Kaktovik, Alaska** is focusing on long-term ecological observations in a single type of environment. The projects **GreenEdge Project** in Baffin Bay has just finished and **NASA ABoVE** in western Canada and Alaska is well underway, but their results can be upscaled. **DOE HiLAT** is developing knowledge about Arctic deltaic systems as a buffering interface between terrestrial and marine ecosystems, in close collaboration with the **DOE TES-funded NGEE-Arctic**, and the **DOE RGMA RUBISCO** projects, which address high-latitude biogeochemistry from a terrestrial perspective.

The proposed **DOE InteRFACE** project is a modeling-based effort that plans to address many of the physical drivers for change across the land-ocean-sea ice interface in the Arctic. The goal will be to quantify how changing inputs to the coastal ocean, landfast sea ice distributions, and ocean stratification will impact biogeochemical cycling in the coastal Arctic, with a particular focus on benthic biogeochemical processes.

Year-round sea and ice biogeochemical processes will be measured in the Central Arctic Ocean by the **MOSAiC project,** and they will be the first to drift along that specific transect. The project has modeling and observation components, including microbial community structure, surface fluxes, and nutrient supply/cycling carried out by NSF-funded researchers among many international teams, with associated (repeat) measurements of nutrient dynamics and ice algal biomass conducted at Utqiagvik, Alaska. Very little is known about biogeochemical processes in the central Arctic Ocean, especially in winter. Sea ice surveys by ship are usually in summer months long after ice algae are gone. MOSAiC seeks to improve Arctic regional and Earth system models by focusing on model-data integration and scaling field design to a high-resolution Earth system grid cell (i.e., 30 x 30 km grid size) yet within the context of further afield and land-based observatories.

Biogeochemistry-Climate feedbacks. DOE's HiLAT-RASM project is studying the impact of fluvial inputs of freshwater and nutrients on high-latitude marine ecosystems, and associated climate impacts. The focus is primarily on elemental cycling of organic matter in rivers and deltas; the consequences of these inputs for marine and sea ice ecosystems in the coastal zone; and climate impacts through surface colorations and marine aerosol emissions in fully-coupled Earth system models.

Regional Biogeochemical Modeling. High resolution (<~10 km horizontal resolution) coupled physical-biological models of the marine ecosystem are being used to explore and understand biogeochemical processes in the high latitude environment. The UAF modeling group, in collaboration with colleagues at NOAA/PMEL, two-way coupled the Regional Ocean Modeling System **(**ROMS) hydrographic model to a lower trophic level ecosystem model with ice algae and benthic components. F . The coupled physics-biogeochemistry model has been used to primarily address change/variability in primary and secondary productivity and food web dynamics in the Bering Sea. With recent additions of carbonate dynamics and oxygen, (University of Washington/PMEL) future work will consider multiple stressors on the marine ecosystem (e.g., rising temperature + acidification + low oxygen). The model can be expanded to cover the entire Arctic Ocean. Researchers at UAF, WHOI and international scientists are also using, respectively, ROMS-type (e.g., COBALT-ROMS) and other high spatial resolution models in the Arctic (e.g., Norwegian and German groups using the 3D-nested SINMOD). A 5 km COBALT-ROMS covering the Chukchi and Beaufort Seas is being readied to study the impact of OA and climate change on inorganic carbon dynamics and ecosystems, as well as a pan-Arctic COBALT-ROMS run explicitly forced with riverine point sources.

Regional Arctic System models with marine biogeochemistry. The high resolution Regional Arctic System Model (RASM), funded by DOE and run from the Naval Postgraduate School, was developed to advance capability in simulating critical physical processes, feedbacks and their impact on the Arctic climate system and to reduce uncertainty in its prediction. A streamflow routing model was recently implemented in RASM to transport the freshwater flux from the land surface to the Arctic Ocean. In addition, marine biogeochemistry components with a lower trophic NPZD model with ice algae have been implemented in the ocean and sea ice components to expand RASM capability into Arctic ecosystem studies. The coupled physics-biogeochemistry model has been tested in the Bering and Chukchi Seas.

Rate measurements. The **Arctic Integrated Ecosystem Research Program (AIERP)** includes a UAF project called **Arctic Shelf Growth, Advection, Respiration, and Deposition Rate Experiments (ASGARD)** that will provide measurements of the rates of temperature-dependent biological processes in the northern Bering and Chukchi Seas that are needed to develop models. Rates will be provided for primary and secondary producers (i.e., phytoplankton and zooplankton) that form the base of Arctic food web. Species-specific respiration rates will be provided for a variety of organisms, including zooplankton and benthic invertebrates, that will allow ecosystem models to explore the effects of changes in community composition. Modeling temperature-dependent shifts in the abundance and longevity of lipid-rich zooplankton in the marine ecosystem could allow prediction of the abundance and condition of higher trophic level species like fish, seabirds, and marine mammals.

Ecosystem connections. The NPRB Long-term Monitoring Program funds the CFOS-UAF-led **Chukchi Sea Ecosystem Observatory (CEO)**. The observatory consists of a set of closely located moorings in the Chukchi Sea that will provide long-term datasets (2014 - 2024) of temporal variations in sea ice cover and thickness, light, currents, waves, water column structure, and concentrations of dissolved oxygen, nitrate, inorganic carbon species, and particulate matter. They document the presence of phytoplankton blooms and export, zooplankton abundance and vertical migration of Arctic cod and other fishes, and the vocalizations of marine mammals. The datasets will allow for a better year-round understanding of teleconnections throughout the ecosystem and will therefore be invaluable to evaluate and improve biogeochemical models.

Model evaluation through comparisons with observations. Model-data intercomparisons are already a common part of the Arctic marine biogeochemical modeling culture and important for both advancing simulations and building community. **FAMOS** has helped facilitate several of these studies. The growing number of Arctic data compilations for biological variables (nutrients, chlorophyll, primary production) that are openly available to the modeling community can help support future detailed exploration of Arctic marine biogeochemical model responses and their underlying drivers, for example, through IOMB diagnostic packages provided by **DOE RGMA RUBISCO**.

Knowledge Gaps

Processes at the terrestrial/ocean interface. The presence/absence and stability of landfast ice play an integral role in coastal biogeochemistry. Sea ice properties (physical and chemical), riverine carbon, and sediment fluxes impact algal blooms, e.g., through light attenuation. In the shallow nearshore environment, ice gouging or wave action (e.g., winds) can also impact the light environment through resuspension, as well as influence energy support for marine consumers through mechanical disturbance. In addition to marine primary production, terrestrial organic matter (TOM) provides a basal energy source for marine consumers. *Landfast ice and, for the most part, bottom sediments are missing from regional and Earth system models. Organic matter processing along the land-ocean continuum is not well understood.*

Seasonality and interannual variability. Much of our current knowledge on which our models are based is biased toward the summer season, especially when conditions are most favorable for making measurements. But winter does not mean zero activity; polar night processes (mixotrophy; zooplankton and upper trophic levels) continue. There exist a few valuable yet limited biophysical datasets spanning years-decades (e.g., **NOAA PMEL's Bering Sea moorings**; **CEO since 2014**). We need more measurements to record seasonality and changes (see Research Needs and Opportunities – Observations). *As understanding of marine coastal processes during winter and "shoulder seasons" (i.e., winter-spring and summer-fall) improve and representations are incorporated in Earth system models, it will provide a more holistic/realistic view of the Arctic system.*

Marine ecological processes that affect upper trophic level species. The **Bering Sea Integrated Ecosystem Research Program (BSIERP)** and the **Gulf of Alaska Integrated Ecosystem Research Program** illustrated how observational data combined with modeling can provide valuable insights into marine ecological processes that affect upper trophic level species including commercially important fish. For example, temperature-dependent growth and condition of phytoplankton and zooplankton can be used to predict the survival of fish like pollock and cod. In Alaska waters, the NOAA has documented northward shifts of commercial fish species in the Bering Sea in recent years. *Modeling marine ecological processes may inform the mechanisms driving species shifts and allow prediction of future conditions under various climate scenarios.*

Research Needs and Opportunities

Observations. Regional and Earth System Models can be used to synthesize knowledge and extend the utility of observations beyond their spatiotemporal constraints, but the lack of consistent field sampling across the Arctic coastal system is hampering the development of Arctic coastal ocean components. Critical observational needs include:

- ⇨ Year-round or continuous surface and subsurface biophysical observations representative of study area(s) that are of sufficient sampling frequencies to capture significant changes (see NASA's Arctic-COLORS Science Plan);
- ⇨ Observations of the timing and magnitude of terrestrial fluxes from deltas, coastal erosion, and nonpoint source input of water;
- ⇨ Development of sea ice-"resilient" observing platforms (e.g., building on the successes of year-round ITP, O-Buoy, WARM, IMB, UpTempo deployments; testing of Carbon Dioxide Seaglider);

- ⇨ Development or deployment of biogeochemical buoy systems that can take advantage of sea ice and survive in open water when ice melts for long-term, seasonal observations (e.g., O-Buoys, WARM);
- ⇨ Development of the same as above but at the even harsher landfast/river freshet to sea ice/open seawater interface;
- ⇨ Important sources of uncertainty in observations (alongside their uncertainty in predictions);
- ⇨ Access to observational data and opportunities in the Russian Exclusive Economic Zone;
- ⇨ Evaluation and improvement of NASA satellite remote sensing retrievals in the complex, coastal Arctic region, to enable the development of new applications for existing sensors as well as provide a robust dataset required to develop applications for the next generation of NASA satellite missions (see NASA's Arctic-COLORS Science Plan).

Synthesis data. Several projects have collected Arctic marine observational data that could be used to develop and validate models. The **Pacific Marine Arctic Regional Synthesis (PacMARS)** project organized four decades worth of data/metadata on physical and chemical oceanography, phytoplankton, zooplankton, and benthic ecology that include information about biodiversity and community composition in the northern Bering, Chukchi, and Beaufort Seas. The **NSF ARCSS-PP and NASA Arctic Ocean PPARR** compiled and quality-checked nutrient, chlorophyll, primary production and light parameters observations (1959-2011) for the pan-Arctic, now openly available at **NOAA National Center for Environmental Information (NCEI)**.

Databases. There is a need for making data more accessible and available in a format most useful for modelers. Observational data from different groups often have their own formats and naming schemes making encoding of the data tedious and time consuming. Standardized data formats should avoid repeated and duplicated efforts by different modeling groups who use the data. A basic CF compliant dataset is the most useful format for modelers. Data should be four-dimensional (time, latitude, longitude, and depth) with all of the variable names and abbreviations following CMIP5/CMIP6 convention. Similarly, biogeochemical model predictions would benefit from transparent, reproducible, and accessible modeling products, which make data, code, and models easier to access, understand, and reuse. Current trends are making data and code openly available. Best practices in data structure, metadata, and software development should be followed.

Model integration of data (i.e., new parameters/processes) is needed and can be very time consuming (i.e., runs, tuning) and therefore requires careful planning. A central question to model development is which biological parameters are most sensitive.

Ongoing and planned observational campaigns are bringing modelers, observers, and remote-sensing investigators together. NASA's Arctic COLORS and MOSAiC both offer the opportunity to bring a wide range of international expertise and experience together in the planning stage, and throughout deployment, data analysis, synthesis, and interpretation.

The AIERP (2016-2021) will collect a wealth of biological data coincident with oceanographic data. A synthesis phase is planned to begin in 2022 that may include modeling projects that will use existing data to predict future marine ecological conditions. North Pacific Research Board has committed $1 M to this synthesis and is seeking funding partners. The scope of the synthesis will depend on the funding available to support it.

Recommended Next Steps

With this white paper as motivation and guidance, we need to build on the successes and lessons learned from past research projects with the goal of bringing modelers and observers together, such as BSIERP. A workshop to broaden the discussion would be beneficial, where the efficacy of approaches and recommendations from this white paper would be shared and discussed more broadly. The overall goal of such a workshop would be to garner community input and buy-in on how to exploit a growing suite of observations to evaluate and improve ice-ocean biogeochemical processes in Arctic regional and Earth system models, especially for the Arctic marine coastal zone. Focal points for discussion would include key science questions, pressing observational and model development needs, links with existing observational networks, model-measurement synthesis activities, and data center needs. To this end, we propose a 3-day workshop bringing together ~45 invited participants from observational, modeling, remote sensing, and data management communities, as well as agency managers and key international participants. Desired outcomes and deliverables would include: (1) a revised and completed Table 1 (i.e., draft Table 1 in Appendix) identifying and prioritizing processes key to understanding the controls on marine biogeochemical processes in the Arctic coastal zone, (2) a peer-reviewed manuscript, and (3) a formal workshop report that would document the discussions, summarize a community synthesis, and include recommendations for program managers.

Suggested Reading

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and references therein.

Osborne, E., J. Richter-Menge, and M. Jeffries, Eds., 2018: Arctic Report Card 2018, https://www.arctic.noaa.gov/Report-Card and earlier years as well.

For more suggestions, contact lead author, C. Deal, cmdeal@alaska.edu.

Appendix:

Table 1*: Draft table of potential processes/features targeted in potential workshop deliberations (to be developed by a Workshop Organizing Committee).*

Process/Key feature	**Priority/Urgency/Maturity**	**Variables/Data sources**
Pan-Arctic and regional trends and drivers of environmental change e.g.: Coastal erosion, river input, subsea permafrost thaw etc.	Workshop participants identify: - Scientific priority level - Urgency w/r to model performance criteria - Maturity w/r to scientific understanding, technology etc.	Workshop participants identify variables for benchmarking, relevant data sources etc.
Ice-ocean-atmosphere interaction e.g.: Air/sea/ice gas exchange; release of nutrients & organics	…	…
Biogenic aerosol emissions and cloud responses, e.g., Dimethyl Sulfide (DMS), marine organics through sea spray	…	…
Light environment e.g.: Changes in surface spectral fluxes, snow cover, melt ponds, sediment & biological inputs	…	…
Biological processes/features e.g.: Timing of spring bloom, mis/match of primary & secondary production, subsurface organic matter remineralization	…	…

Greenhouse gas fluxes/budgets e.g.: methane release from thawing subsea permafrost, sediment respiration of CO_2, methanogenesis, carbonate system, etc.	…	…

***Table 2**: Arctic-COLORS Table 5.3. Past and current projects in the coastal Arctic Ocean relevant to the Arctic-COLORS goals (*From *Arctic-COLORS Science Plan* https://arctic-colors.gsfc.nasa.gov/docs/ArcticCOLORS_Science_Plan_draft_January2018.pdf*).*

Program	Funder	Years (in field)	Region	Goals
Inner Shelf Transfer and Recycling Project (ISHTAR)	NSF	1980s	N Bering and Chukchi Seas; relatively small role played by Yukon R.	Processes overall high productivity; physical, chemical, microbial data; no optical data
National Water Information System	USGS/ BLM/ USFWS/ NSF	1994 or more recent - present	Four stations along nearshore S. Beaufort Sea	River gauges, river discharge, precipitation, air temperature
Outer Continental Shelf Environmental Assessment Program	Industry	2000s	Chukchi Sea	monitoring predating oil development; physical, chemical, limited microbial data; no optical data
Chukchi Sea Environ-mental Studies Program	Industry	2000s	Chukchi Sea	physical, chemical, limited microbial data; no optical data
Chukchi Offshore Monitoring in Drilling Area program	BOEM	2000s	Chukchi Sea	physical, chemical, limited microbial data; no optical data
Shelf-Basin Interactions	NSF	2000-08	Beaufort Sea shelf - Arctic Basins	exchange of organic materials and water masses from the shelf to the deep basin; physical, chemical, microbial data; extensive optical data
Canadian Arctic Shelf Exchange Study (CASES)	Canada	2002–2004	near the Mackenzie River shelf	multidisciplinary and seasonal, through-the-winter coverage of the region; physical, chemical, microbial data; some optical data

Russian-American Long-term Census of the Arctic (RUSALCA)	NOAA	2003-16	Bering Strait and Chukchi Sea	physical, chemical, microbial data; no optical data
Study of the Northern Alaska Coastal System (SNACS)	NSF	2005-08	Bering Strait, S Chukchi Sea, S Beaufort Sea	5 loosely coordinated projects that studied either terrestrial or marine systems, but rarely both; physical, chemical, microbial data; no optical data
Circumpolar Flaw Lead Study (CFL)	Canada	2007-2008	near the Mackenzie River shelf	multidisciplinary and seasonal, through-the-winter coverage of the region; physical, chemical, microbial data; some optical data
MALINA	France-Canada	2009	S. Beaufort Sea and the shelf adjacent to Mackenzie river outlet in late summer	light controls of biodiversity and biogeochemical fluxes; physical, chemical, microbial data; extensive optical and remotely sensed data
Bering Sea Project	NSF, NPRB	2010s	Bering Sea	integrated ecosystem understanding; physical, chemical, microbial data; no optical data
Impacts of Climate on the Eco-Systems and Chemistry of the Arctic Pacific Environment (ICESCAPE)	NASA	2010-2011	Chukchi Sea shelf-basin (marginal ice zone, pack ice)	Biological productivity as a function of changing light transmission and sea ice conditions; physical, chemical, microbial data; extensive optical data
Beaufort Gyre Observatory Project	NSF, WHOI	2002-2018	Beaufort Sea, Canadian Arctic	Ice-tethered profilers and sediment traps; physical, chemical data; some optical data.
Distributed Biological Observatory (DBO)	NOAA, IARPC	2010-2018	Bering, S. Chukchi, SW Beaufort Seas	Pelagic-benthic interactions; physical, chemical, microbial data
Next Generation Ecosystem Experiments (NGEE)-Arctic	DOE	2012-14; 2015-18	North Slope Alaska; Seward Peninsula, AK	Terrestrial carbon, water, nutrient, and energy fluxes for earth system models
Chukchi Sea	NPRB	2017-2018	Chukchi Sea	integrated Arctic ecosystem project; physical, chemical, microbial data

Polar Knowledge Canada (POLAR)	Canada	2014-2019	Cambridge Bay, Nunavut (CHARS) and surrounding areas	impacts of changing ice, permafrost and snow on shipping, communities and infrastructure
Arctic Great Rivers Observatory	NSF	2004-2019	Yukon and Mackenzie Rivers	Extensive physical and chemical data
Marine Arctic Ecosystem Study (MARES)	BOEM, NOPP	2016-2019	E. Beaufort Sea, Mackenzie River plume	Under-ice and across-shelf distribution and biogeochemical impacts; physical, chemical, microbial data
Arctic Boreal Vulnerability Experiment (ABoVE)	NASA	2015-2021	N. Alaska-Canadian Arctic	Carbon cycling in terrestrial and hydrological systems; extensive remotely sensed land data
Sentinel North	Canada	2015- 2022	Canadian Arctic	Autonomous photonics and human health observations
The Beaufort Sea Lagoons (BLE-LTER)	NSF	2017-2022	Beaufort Sea coastal lagoons	Coastal ecosystems, shoreline erosion, watershed runoff, sea ice dynamics, continuous seasonal and interannual observations